V. Head Construction

Many substrates have been tested such as oxidized silicon, aluminium coated with alumina, glass, etc. The glass substrate offers large mechanical hardness. Many heads are aligned on the same substrate using only one mask. The wire convections are then soldered, and heads are covered with a protective coating. Separated heads or whole head group are cut, and the plane facing the recording medium is obtained by grinding with a diamond wheel. Fig. 8 shows a gap and the pole faces of multilayer legs.

VI. Conclusions

We have seen that the present integrated magnetic head offers many advantages over classical heads: mass production, miniaturization, efficiency, and very large frequency bandwidth. Fig. 9 shows an integrated magnetic head. In spite of the fact that the write current is still too high ($I_w < 500$ mA), the results are very encouraging. New possibilities are opened by this head model; with an appropriate thickness distribution of the magnetic films which form the multilayer leg, it may be possible to determine a potential function at the pole faces of the magnetic legs. (In a classical head, this potential function is fixed and assumed to be an equipotential.)

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A Magnetoresistive Readout Transducer

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Abstract—A new type of reproduce transducer for reading magnetically recorded tapes is described. The device structure, which utilizes the magnetoresistive effect in a thin magnetic film deposited onto a nonmagnetic substrate, provides wavelength response characteristics comparable to existing technology. Indigenous noise effects are subordinate to tape noise. No intrinsic frequency limitations are experienced for recording bandwidths in existence today. Since the device detects the tape's fringing fields directly, the output is not a function of tape velocity. The device construction lends itself nicely to multichannel head assemblies. The transducer may also be used to detect digitally recorded information.

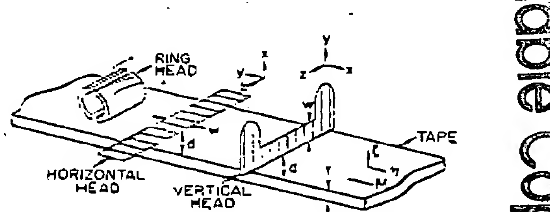

Fig. 1. Horizontal and vertical head configurations.

Introduction

A NEW type of transducer which reads stored magnetic information and performs comparably to ring type heads conventional to magnetic recording is described. The device makes use of the magnetoresistive effect in thin magnetic film strips which are deposited onto a nonconductive substrate. Two possible geometries are indicated in Fig. 1. The plane of the film strip may lie either parallel to the plane of the storage medium (horizontal configuration) or perpendicular to the plane of the storage medium (vertical configuration). From the point of view of wear resistance, the vertical structure is preferred since the substrate then takes the brunt of the abrasive action caused by the relative motion between transducer and storage structure.

In magnetoresistive materials, such as unoriented polycrystals with isotropic resistance, the resistivity ρ has a uniaxial anisotropy with a symmetry axis parallel to the direction of magnetization [1]. Thus

$$\rho = \rho_0 + \Delta\rho \cos^2\theta \qquad (1)$$

where ρ_0 is the isotropic portion of the resistivity, $\Delta\rho$ is the magnetoresistivity, and θ is the angle between the magnetization M and the current density vector. For materials such as Permalloy and cobalt–iron alloys, $\Delta\rho$ amounts to about 2–6 percent of ρ_0 at room temperature [2]. In the geometry of Fig. 1, the fringing fields of the stored information operate on the magnetization of the film strip to cause a variation in the angle θ. By supplying the device with a constant current, a terminal voltage proportional to $\cos^2\theta$ arises.

To describe the device's operation analytically, a functional relationship between the applied field H and the

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angle θ is required. By assuming that the cross section is elliptical so that the film's demagnetizing field NM_y is uniform, and by assuming that there is an anisotropy field H_k parallel to the current density vector, one may relate the orientation of the magnetization to the applied fields. For simplicity we shall assume that demagnetizing effects render x field components ineffective. We shall also assume that there are no z field components.

Using the usual principles of minimization of the free energy one can show that

$$-H_y \cos\theta + H_0 \sin\theta \cos\theta = 0 \qquad (2)$$

where

$$H_0 = H_k + NM, \qquad (3)$$

thus

$$\sin\theta = \frac{H_y}{H_0}.$$

The variation of resistivity becomes

$$\rho = \rho_0 + \Delta\rho\left(1 - \frac{H_y^2}{H_0^2}\right). \qquad (4)$$

To linearize this result we let H_y be composed of a dc bias field H_b and a tape signal field h_y. Thus

$$\rho = \rho_0 + \Delta\rho\left(1 - \frac{H_b^2}{H_0^2} - \frac{2H_b h_y}{H_0^2} - \frac{h_y^2}{H_0^2}\right). \qquad (5)$$

The resistivity may be integrated over the device dimensions to get a signal voltage V

$$V = 2IR_0 \frac{\Delta\rho}{\rho_0}\frac{H_b}{H_0^2}\iint h_y(y,z)\,\frac{dy}{W}\,\frac{dz}{L}. \qquad (6)$$

We ignore the constant and quadratic terms. R_0 is the bulk resistance of the element. L is the length of the element measured in the direction of current flow and W is the depth of the element. The device essentially responds to the applied fields averaged over the head dimensions.

The bias field H_b is also a measure of the maximum field that may be linearly detected. For an elliptical cross section, N is simply the ratio of thickness to depth $4\pi\Delta/W$ provided that $\Delta/W \ll 1$. Control of the aspect ratio regulates the dynamic response of the device to y-directed fields, as seen in the experimental curves appearing in Fig. 2 for a 2000 Å thick film. Observe in these curves that the approach to saturation is gradual rather than abrupt, as expected in the Stoner–Wohlfarth model. Since the cross section is in fact more nearly rectangular, inhomogeneous demagnetizing effects substantially round off the curves at high fields, leaving a point of inflection. This fact makes the preceding analysis only approximate. The experimental dependence of an experimentally defined demagnetizing field on film thickness and element depth for Permalloy films is shown in Fig. 3. The demagnetizing field for the purposes of this paper was considered to be the value taken at the point of inflection of the ΔR versus H characteristic (Fig. 2), and hence is also the optimum bias field H_b since this point will obviously minimize second harmonic distortion and provide maximum dynamic range.

As an example, consider a Permalloy ribbon which is 50 mil long, 0.6 mil deep, and 2000 Å thick. The resistance of the strip is about 200 Ω and the magnetoresistance is about 2 percent or 4 Ω. A device of this description can readily handle a measuring current of 20 mA, making available a peak-to-peak (p–p) signal capability of about 80 mV. The bias field required for this geometry is about 80 Oe, which should in no way influence the storage medium.

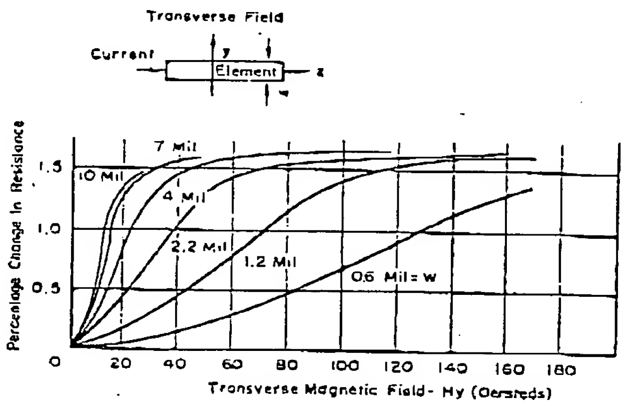


Fig. 2. Magnetically induced change in resistance versus transverse applied field H_y for various depths W. Film thickness was 2000 Å. Curves are experimental.

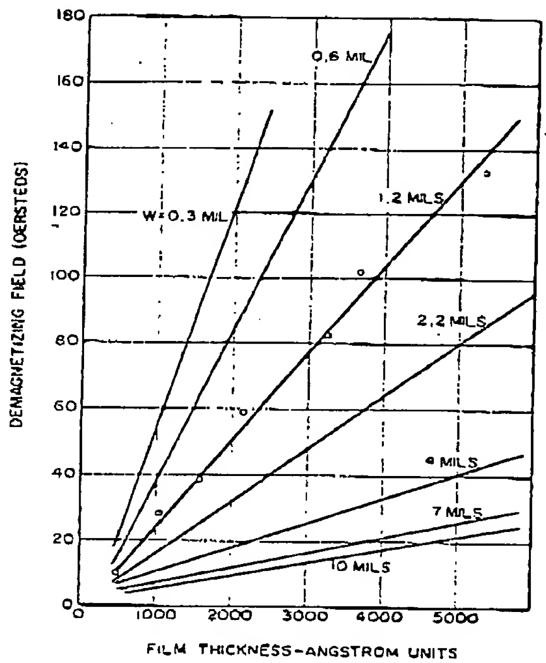


Fig. 3. Experimental variation of optimum bias field H_b (demagnetizing field) with thickness and element depth for thin films of Permalloy.

The magnetoresistive elements described in Figs. 2 and 3 were made by masked evaporation of Permalloy onto a glass substrate. Subsequently elements of various depths W were photoetched.

Sine Wave Response

The wavelength response of the magnetoresistive head (MRH) may be readily calculated if it is assumed that the storage medium is uniformly magnetized in the plane of the tape according to $M = M_r \sin k\eta$ (η and ζ are coordinates natural to the tape while x, y, and z coordinates are natural to the head geometry). Wallace [3] has shown that the horizontal and vertical components of the field above the tape are

$$\begin{pmatrix} h_x \\ h_y \end{pmatrix} = -2\pi M_r e^{-k\zeta}(1 - e^{-kt}) \begin{pmatrix} \sin k\eta \\ \cos k\eta \end{pmatrix}. \qquad (7)$$

ζ is the coordinate normal to the medium's surface, while η runs along the tape's length; t is the tape's coating thickness. The origin of coordinates is so chosen that $\zeta = 0$ corresponds to the surface of the tape. k is the recorded wave vector ($2\pi/\lambda$) and η is simply the time–velocity product vT. It is a simple matter to let (6) operate on (7) to yield the responses for the two geometries

$$\begin{pmatrix} V_{hor} \\ V_{ver} \end{pmatrix} = IR_0 \frac{\Delta\rho}{\rho} \frac{4\pi M_r H_c}{H_0^2} e^{-kd}(1 - e^{-kt}) \cdot \begin{pmatrix} \dfrac{2\sin(1/2kW)\,\sin kvT}{kW} \\[2ex] \dfrac{(1 - e^{-kW})}{kW}\cos kvT \end{pmatrix}. \qquad (8)$$

Examination of (6) shows that 1) the MRH response is independent of tape velocity ($\eta = vT$), 2) the horizontal MRH exhibits an interference phenomenon analogous to the usual gap loss, 3) the vertical head shows no gap interference term since the film thickness is so small, 4) both configurations show the usual coating thickness dependence, 5) both configurations exhibit the usual dependence on head-to-tape spacing d.

A number of heads of both the horizontal and vertical configuration were fabricated and tested. Horizontal MRH devices were made by photoetching elements from evaporated Permalloy on glass substrates. Vertical MRH devices, on the other hand, were fabricated by evaporation through a mask onto the edge of a carefully polished glass slide.

An example of the response for a vertical MRH is shown in Fig. 4. Unbiased sine wave recording was used; the record current was optimized at each wavelength. At the response maximum the rms output was about 25 mV. The head resistance was about 500 Ω, and a head current of 10 mA was utilized. Equation 6 is plotted on top of the experimental curve, assuming a head-to-tape spacing of 25 μin, an element depth of 0.5 mil, and a tape coating thickness of 300 μin. The data was taken at

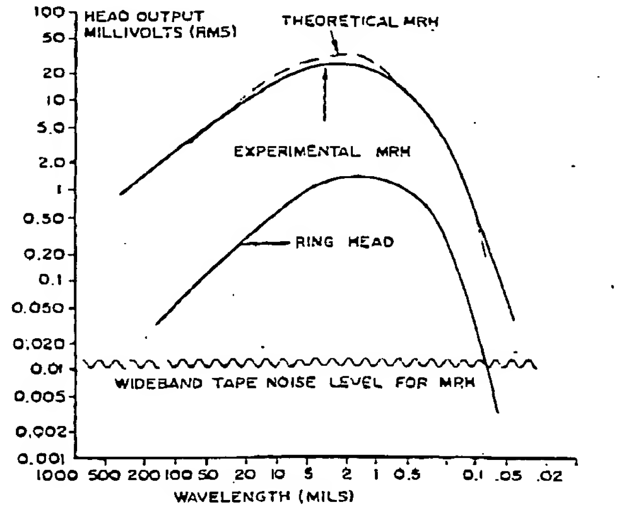


Fig. 4. Theoretical and experimental response of vertical magnetoresistive head compared to ring head response.

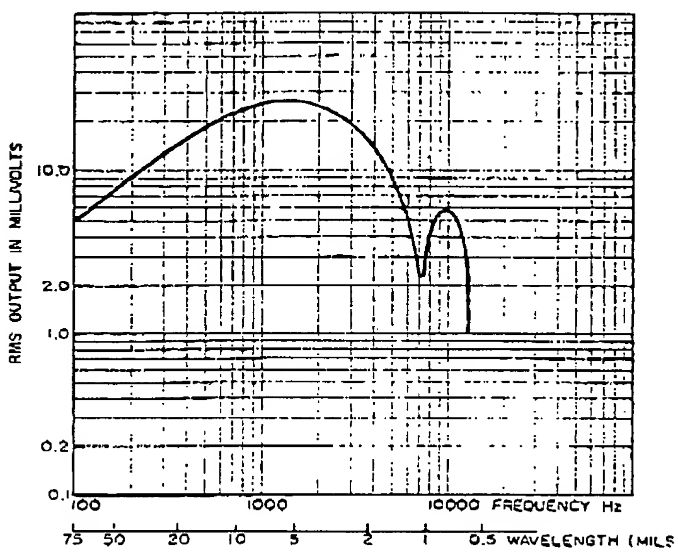


Fig. 5. Experimental response characteristic of horizontal magnetc resistive head. Head was 70 mil long, 350 Å thick, and 1.2 m deep.

$7\frac{1}{2}$ in/s with an 100 kHz electrical bandwidth and a trac width of 50 mil. The rms tape noise level indicated i the figure is about 67 dB below the response maximum Johnson noise is ignorable. The response of an instru mentation type ring head to the same recording, with gap length of 35–40 μin, a gap depth of 7 mil, and 6 turns, is shown also.

Fig. 5 shows the experimental response function of horizontally disposed magnetoresistive element whic has an element depth of 1.2 mil. This data was take at $7\frac{1}{2}$ in/s. Due to wear problems, however, the hor zontal MRH is not of practical significance for mos applications.

Noise and Crosstalk Characteristics

The only noise sources intrinsic to the MRH are 1) Johnson noise, 2) mechanically induced magnetostrictive noise, 3) thermal variations in the element's resistance. No evidence of mechanically induced magnetostrictive noise was seen for the films used here. Thermal variations of the element's resistance produce low frequency noise components (<1 kHz) unless both sides of the element are protected from air convection (by, for example, sandwiching between two pieces of sapphire), in which case thermal fluctuation noise is not important. Johnson noise is a Gaussian distributed white noise source with an rms voltage given by

$$E_n = \sqrt{4kTR\Delta f} \tag{9}$$

where k is Boltazmann's constant, T the absolute temperature, R the element's resistance, and Δf the bandwidth. For a 500 Ω element having a $\Delta\rho/\rho$ of 2 percent, supporting a 10 mA current, and operaitng into a 1 MHz bandwidth, the maximum possible ratio of p–p signal to rms Johnson noise is $IR(\Delta\rho/\rho)/\sqrt{4kTR\Delta f}$. For the numbers mentioned this ratio is about 7×10^4 or 97 dB at room temperature.

The principal noise source is tape noise. In an analysis paralleling Mallinson's [4] assuming that the magnetization of a demagnetized oriented tape does not correlate with itself, (i.e., the autocorrelation function in the spatial coordinates ζ, η, z is a 3-dimensional impulse function), one may show [5] that the ratio of p–p signal $I\Delta R$ to rms tape noise is as shown in (10) where M_r is the remanent moment of the tape, ΔV is the elemental volume of a tape particle. Taking a head-to-tape spacing of 0.020 mil, an elemental particle volume of 10^{-14} cm_3, a coating thickness of 300 μin. and a ratio of $H_B/4\pi M_r = 0.20$ (for linearity), and further assuming the head dimensions $L = 50$ mil and $W = 0.6$ mil, one gets a wideband signal-to-noise ratio of about 80 dB. Fig. 4 shows a p–p/rms ratio of about 7000/1 or 77 dB.

$$\frac{S(\text{p–p})}{N(\text{rms})} = \frac{H_b}{4\pi M_r}\left[\frac{8\pi L W^2}{\Delta V \log\{[1 + t/(d + W)]\,(1 + t/d)/[1 + t/(d + (w/2))]^2\}}\right]^{1/2} \tag{10}$$

Another point of interest is the sensitivity of the MRH to crosstalk effects. An MRH characterized by a length of 70 mil, depth W of 2.5 mil and thickness Δ of 1000 Å was located 10 mil (at point of closest approach) from a recorded track 50 mil wide. The crosstalk signal was maximum at a recorded wavelength of 50 mil and was about 45 dB below the signal level derived from a 50 mil wavelength signal recorded directly below the MRH. An approximate formula for rms ratio of signal to crosstalk, valid for wavelengths in excess of 1 mil may be shown to be [5]

$$\frac{\text{rms signal}}{\text{rms crosstalk}} \simeq \frac{4\pi^2 L}{\lambda \int_{2\pi D/\lambda}^{\infty} K_0(\nu)\,d\nu} \tag{11}$$

where $K_0(\nu)$ is a modified Bessel function of the second kind and D is the intratrack guardband. Evaluating this integral [6], one finds that the crosstalk should be about 42 dB down for the preceding configuration.

Digital Detection

The MRH transducer also may be used for detection of digitally recorded bits. If the magnetization of the tape is assumed to be a step function of value $2M_r$, and if tape demagnetizing effects are ignored, the ζ component of field above the tape is

$$H_\zeta(\zeta) = 2M_r \log\left[\frac{(\zeta + 1/2t)^2 + \eta_0^2}{(\zeta - 1/2t)^2 + \eta_0^2}\right] \tag{12}$$

where t is the coating thickness and η_0 measures the distance between head and transition. The coordinate reference is the center of the tape.

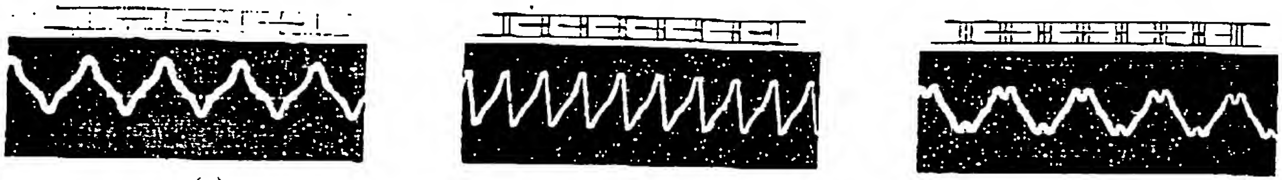
Allowing a head-to-tape spacing d and integrating over the head width W one achieves for an output voltage pulse in terms of $\eta_0(=vT)$

$$\begin{aligned} V = 4IR_0 \frac{\Delta\rho}{\rho_0}\frac{H_b}{H_0^2} M_r \Bigg[& \log\left\{\frac{(d + W + t)^2 + \eta_0^2}{(d + W)^2 + \eta_0^2}\right\} - \frac{d}{W}\log\left\{\frac{(d + W)^2 + \eta_0^2}{d^2 + \eta_0^2}\right\} + \frac{(d + t)}{W} \\ & \cdot \log\left\{\frac{(t + d + W)^2 + \eta_0^2}{(t + d)^2 + \eta_0^2}\right\} - \frac{2\eta_0}{W} \\ & \cdot \left\{\tan^{-1}\frac{W\eta_0}{\eta_0^2 + (d + W)d} - \tan^{-1}\frac{W\eta_0}{\eta_0^2 + (t + d)(t + d + W)}\right\}\Bigg]. \end{aligned} \tag{13}$$

This complicated function basically describes a pulse which peaks at $\eta_0 = 0$ and which decays out to zero for $\eta_0 \gg d + W + t$.

An example of the response to nearly isolated transitions is seen in Fig. 6(a). The horizontal scale is calibrated in terms of distance along the tape. The recording made use of a nonreturn to zero IBM (NRZI) format in which a ONE is a transition, while a ZERO is no transition. The MRH used in this experiment had $W = 2.5$ mil, $\Delta = 1000$ Å, and $L = 70$ mil.

The first pattern of Fig. 6 is a rather broad pulse due to a single transition occurring every 8 mil (1000 bit/in). For two adjacent transitions the pulse shape changes significantly, because now equal amounts of positive and negative charge are packed closely together. Next, for 3 adjacent ONES the bit pattern again resembles the case of a solitary one with an added cusp. Pulse localization is improved by fabricating heads with smaller depth W.



(a) (b) (c)

Fig. 6. Output pulses for various digitally recorded patterns of magnetization. Device was 2.5 mil deep, 70 mil long, and 1000 Å thick. Bit sequence is indicated. Scope calibration is 2 mV/cm and 1 ms/cm. (a) •00100000 at 1000 bit/in. (b) •00110000 at 100 bit/in. (c) •00111000 at 1000 bit/in (7.5 mil/cm).

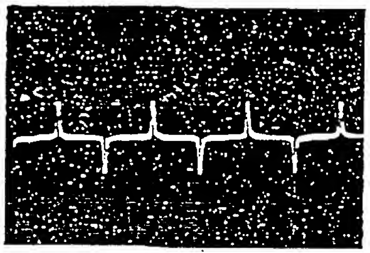


Fig. 7. Ring head response to 100 bit/in digital recording. Horizontal calibration is 7.5 mil/cm.

The magnetization pattern is indicated schematically in the figure for comparison. Fig. 7 shows the output pulse wave form of a ring head detecting isolated transitions occurring every 10 mil along the tape. The reproduce head was the same head described in connection with Fig. 4.

Conclusion

A new type of magnetic transducer for reading magnetically stored information has been described. In sine wave recording, the device's response, output level, noise, and crosstalk characteristics compare favorably to ring head technology. The device may be used to detect digitally recorded information. Since the device is essentially a thin magnetic film, many transducers may be deposited onto a single optically flat substrate to eliminate gap scatter problems in multihead assemblies. The magnitude of the device output is not a function of the tape velocity or frequency. Consequently, a single head is satisfactory for audio, video, or digital applications. Wear characteristics may be controlled by suitable selection of the substrate material. The principal disadvantage to the device is its READ-only capability.

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